New windows on massive stars: asteroseismology, interferometry, and spectropolarimetry
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Probing high-mass stellar evolutionary models with binary stars

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Abstract. Mass discrepancy is one of the problems that is pending a solution in (massive) binary star research field. The problem is often solved by introducing an additional near core mixing into evolutionary models, which brings theoretical masses of individual stellar components into an agreement with the dynamical ones. In the present study, we perform a detailed analysis of two massive binary systems, V380 Cyg and σ Sco, to provide an independent, asteroseismic measurement of the overshoot parameter, and to test state-of-the-art stellar evolution models.

Keywords. asteroseismology, star: oscillations (including pulsations), line: profiles, methods: data analysis, techniques: photometric, techniques: spectroscopic, (stars:) binaries: spectroscopic, stars: fundamental parameters, stars: individual (V380 Cyg, σ Sco)

1. Introduction

One of the major problems that is currently pending a solution in binary star research field is the so-called mass discrepancy problem. It stands for the difference between the component masses inferred from binary dynamics (hereafter, dynamical masses) and those obtained from spectral characteristics of stars and evolutionary models (hereafter, theoretical masses). The mass discrepancy problem observed in massive O- and B-type stars has been known for more than 20 years already and has been discussed in detail by Herrero et al. (1992). Hilditch (2004) pointed out that the discrepancy does not disappear when the effects of rotation are included into the models.

A remarkable mass discrepancy has been reported by Guinan et al. (2000) for the primary components of the V380 Cyg system. The authors showed that large amount of core overshoot (α_{ov} = 0.6 pressure scale height) can account for the difference between dynamical and theoretical mass of the primary component. This large amount of overshoot contradicts the typical value of $\alpha_{ov} <= 0.2$ Hp observed for single stars of similar mass (see e.g. Aerts 2013, Aerts et al. 2003, 2011; Briquet et al. 2011). Moreover, the second largest value after V380 Cyg of α_{ov} ∼0.45 has also been measured in a binary system, for the 8 $M_\odot$ primary component of the θ Ophiuchi system (Briquet et al. 2007). Recently, Garcia et al. (2014) found that convective overshoot α_{ov} >0.35 is required to reproduce observed absolute dimensions of both components of the V578 Mon system. Thus, there seems to be a tendency of measuring larger core overshoot in binary stars than in single objects, within the same stellar mass range. The reason is that this parameter often effectively accounts for the above mentioned mass discrepancy, but we need to investigate the feasibility of using core overshoot alone to explain such a complex problem as discrepancy between dynamical and theoretical masses in binary stars.

In this paper, we present a study of two massive binary star systems, V380 Cyg and σ Sco, and aim at measuring core overshoot parameter for pulsating components using asteroseismic methods.

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Table 1. Key orbital, physical, and atmospheric parameters of the V380 Cyg and σ Sco systems, as derived from our photometric and/or spectroscopic data.

Parameter		V380 Cyg		σ Sco	
		Primary	Secondary	Primary	Secondary
Period,	(day)	12.425719		33.016±0.012	
Periastron passage time,	(HJD)	24 54 602.888±0.007		24 34 886.11±0.04	
Periastron long.,	(degree)	138.4±0.4		288.1±0.8	
eccentricity,		0.2261±0.0004		0.383±0.008	
RV semi-amplitude,	(km s^{-1})	93.54±0.07	152.71±0.22	30.14±0.35	47.01±0.98
Mass,	($M_\odot$)	11.43±0.19	7.00±0.14	14.7±4.5	9.5±2.9
Radius,	($R_\odot$)	15.71±0.13	3.819±0.048	9.2±1.9	4.2±1.0
$T_{\rm eff}$,	(K)	21 700±300	22 700±1 200	25 200±1 500	25 000±2 400
$\log g$,	(dex)	3.104±0.006	4.120±0.011	3.68±0.15	4.16±0.15
v sin i,	(km s^{-1})	98±2	38±2	31.5±4.5	43.0±4.5

2. V380 Cyg

V380 Cyg is a bright ($V = 5.68$) double-lined spectroscopic binary (SB2, Hill & Batten 1984) consisting of two B-type stars residing in an eccentric 12.4 day orbit. The primary component is an evolved star, whereas the secondary just started its life on the main-sequence. Pavlovski et al. (2009) revisited the *U, B, V* light curves obtained by Guinan et al. (2000) and collected about 150 high-resolution échelle spectra using several telescopes. The authors presented a revised orbital solution, and used spectral disentangling technique (Simon & Sturm 1994) formulated in Fourier space (Hadrava 1995), as implemented in the FDBINARY code (Ilijić et al. 2004), to determine disentangled spectra of both binary components. Similar to the results of Guinan et al. (2000), a remarkable mass discrepancy was found for the primary component of V380 Cyg. Moreover, Pavlovski et al. (2009) came to the same conclusion as Hilditch (2004) did, namely that the effects of rotation included into evolutionary models could not fully account for the observed discrepancy.

The discovery of seismic signal in the primary component of V380 Cyg (Tkachenko et al. 2012) opened up an opportunity of obtaining an independent measurement of the overshoot parameter for this binary system. We base our analysis on about 560 days long time-series of high-precision *Kepler* photometry, and about 400 high-resolution, high signal-to-noise ratio (S/N) spectra obtained with HERMES spectrograph (Raskin et al. 2011) attached to 1.2-meter Mercator telescope (La Palma, Canary Islands).

The effects of binarity in the *Kepler* light curve were modelled using the JKTWD wrapper (Southworth et al. 2011) of the 2004 version of the Wilson-Devinney code (Wilson & Devinney 1971; Wilson 1979). The time-series of spectra were analysed with the FDBINARY code to determine spectroscopic orbital solution and disentangled spectra of both stellar components. We found that light curve yields poor constraints on the shape of the orbit, because of strong correlation between eccentricity e and longitude of periastron ω. Since the quantities $e\,\cos\omega$ and $e\,\sin\omega$ are respectively well constrained from photometry and spectroscopy, we constrained the orbital shape by iterating between the two analyses: the light curve was used to determine best fit ω for a given e, and the spectral disentangling to find the best e for a given ω. Analysis of the disentangled spectra delivered accurate atmospheric parameters and individual abundances for both binary components. Table 1 lists some key orbital, physical, and atmospheric properties of this binary system; for more details, reader is referred to Tkachenko et al. (2014a).

Photometric residuals obtained after the subtraction of our best fit model were sub-

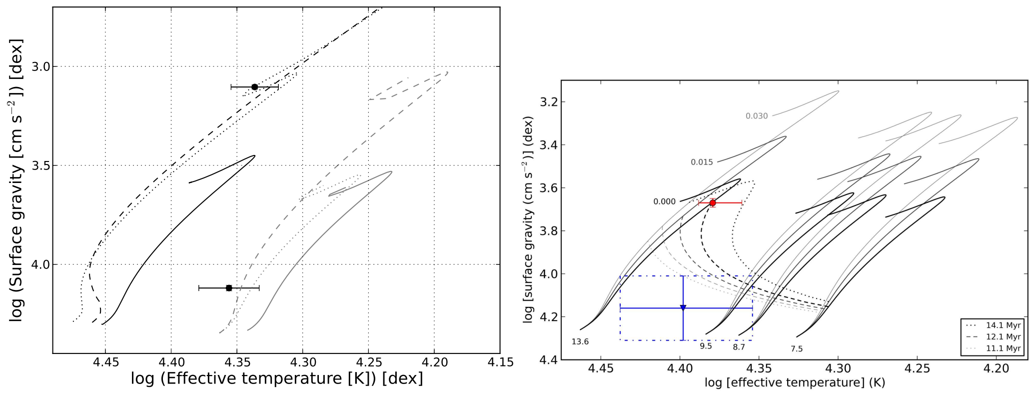

Figure 1. Left: Location of the primary and secondary components of V380 Cyg in the $T_{\rm eff}$-log g diagram. Solid, long- and short-dashed tracks correspond to models 1, 2 and 3 in Table 2, respectively. $T_{\rm eff}$ and $\log g$ values are those from Table 1. **Right:** Position of the primary (circle) and the secondary (triangle) of the σ Sco system in the $T_{\rm eff}$-log g diagram, along with the MESA evolutionary tracks. The initial masses as well as the overshoot parameter f_{ov} are indicated in the plot. The atmospheric parameters $T_{\rm eff}$ and $\log g$ are those from Table 3. The isochrones corresponding to the age of the system of 12.1 Myr and its error bars deduced from seismology of the primary are indicated by the dashed lines.

Table 2. Evolutionary model parameters for both components of the V380 Cyg system. α_{ov} and υ stand for the overshoot parameter and initial rotation rate, respectively.

Parameter		**Primary**			**Secondary**		
		Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
M,	($M_\odot$)	11.43	12.00	12.90	7.00	7.42	7.42
Z,	(dex)	0.014	0.012	0.012	0.014	0.012	0.012
α_{ov},	(H_p)	0.2	0.6	0.3	0.2	0.6	0.2
υ,	(km s^{-1})	0	241	243	0	0	0
Age,	(Myr)	–	21.5	18	–	21.5	18

jected for frequency analysis. The majority of the frequencies are variable both in appearance and amplitude, in agreement with the conclusions made by Tkachenko et al. (2012) about stochastic nature of the signal. The variability consistent with the expected rotation period of the primary component has been detected on top of the binarity and stochastic oscillation signals in the star. We speculate that this signal comes from rotational modulation of spot-like chemical abundance or temperature structures on the surface of the primary component. To verify this hypothesis, spectral line profiles of the primary has been examined for spot signatures, after subtracting the contribution of the companion star from the composite spectra of V380 Cyg. We found a remarkable variability in all observed silicon lines of more massive binary component, which could not be detected in spectral lines of other chemical elements and was found to be consistent with the rotational period of the star. INVERS8 (Piskunov & Rise 1993) code was used to perform Doppler Imaging analysis based on several prominent lines of doubly ionized silicon found in the spectrum of the primary component. The obtained results suggest the presence of two high-contrast stellar surface abundance spots which are located either at the same latitude or longitude.

Finally, we compare our revised fundamental stellar parameters of both components of the V380 Cyg system with the state-of-the-art evolutionary models computed with the MESA code (Paxton et al. 2011, 2013). Figure 1 (left) shows the location of both

Table 3. Fundamental parameters of both components of the σ Sco, after seismic modelling of the primary. Parameters determined spectroscopically are highlighted in boldface.

Parameter		Primary	Secondary
Mass,	($M_\odot$)	$13.5^{+0.5}_{-1.4}$	$8.7^{+0.6}_{-1.2}$
Radius,	($R_\odot$)	$8.95^{+0.43}_{-0.66}$	$3.90^{+0.58}_{-0.36}$
Luminosity ($\log(L)$),	($L_\odot$)	$4.38^{+0.07}_{-0.15}$	$3.73^{+0.13}_{-0.15}$
Age of the system,	(Myr)	12.1	
Overshoot (f_{ov}),	(H_p)	$0.000^{+0.015}$	–
$T_{\rm eff}$,	(K)	$23\,945^{+500}_{-990}$	$\mathbf{25\,000}^{+2\,400}_{-2\,400}$
$\log g$,	(dex)	$3.67^{+0.01}_{-0.03}$	$\mathbf{4.16}^{+0.15}_{-0.15}$

components of V380 Cyg in the $T_{\rm eff}$-$\log g$ diagram along with the evolutionary tracks. The two models that fit the positions of both stars in the diagram, taking into account the error bars, are illustrated by long- and short-dashed lines (models 2 and 3 in Table 2, respectively). The dynamical mass models for both binary components are shown by solid lines (model 1 in Table 2). The MESA model predictions clearly point to mass discrepancy for the primary component, in agreement with the findings by Guinan et al. (2000) and Pavlovski et al. (2009). **We conclude that present-day single-star evolutionary models are inadequate for this particular binary system, and lack a serious amount of near-core mixing.**

3. σ Sco

Sigma Scorpii is a double-lined spectroscopic binary in a quadruple system. Two components are early B-type stars, residing in an eccentric, 33 day period orbit. Though the star was a subject of numerous photometric and spectroscopic studies in the middle of 20th century, its double-lined nature was discovered by Mathias et al. (1991). So far, the studies by Mathias et al. (1991), Pigulski (1992), and North et al. (2007) have been the most extensive ones focusing on orbital and physical properties of the system.

Besides the σ Sco system is a spectroscopic binary, its evolved primary component is known to be unstable to β Cep-type stellar pulsations. Moreover, according to Kubiak (1980), the amplitude of the dominant, radial pulsation mode of the primary is comparable to the orbital semi-amplitude K_1 of this star. This fact was not taken into account in either of the previous studies focusing on orbital solution, but is taken into consideration in our study.

Our analysis is based on some 1000 high-resolution spectra collected with the CORALIE spectrograph attached to the 1.2-meter Euler Swiss Telescope (La Silla, Chile). Orbital parameters of the system were initially derived based on an iterative approach, and further on refined using the method of spectral disentangling. The spectral disentangling was applied to a couple of dozen carefully selected spectra and corresponding to a zero pulsation phase (unperturbed profile), since the method assumes no variability intrinsic to stellar components forming a binary system. For more details on the procedure, reader is referred to Tkachenko et al. (2014b). The disentangled spectra were used to determine accurate atmospheric parameters and chemical composition of both stars. The final set of orbital parameters as well as the spectroscopically derived values of $T_{\rm eff}$ and $\log g$ are given in Table 1. The masses and radii listed in this table were determined from our orbital parameters and interferometric value of the orbital inclination angle reported by North et al. (2007).

We further made use of the fact that the primary component of σ Sco is a radial mode pulsator, and performed asteroseismic analysis of this star. Evolutionary models were computed with the MESA code, while p- and g-mode eigenfrequencies for mode degrees $l = 0$ to 3 have been calculated in the adiabatic approximation with the GYRE stellar oscillation code (Townsend & Teitler 2013). The addition of the seismic constraints to the modelling implied a drastic reduction in the uncertainties of the fundamental parameters, and provided an age estimate (see Table 3). Figure 1 (right) shows the position of both components of the σ Sco system in the $T_{\rm eff}$–$\log g$ diagram, along with the evolutionary tracks. The error bars are those obtained from the evolutionary models and 3σ spectroscopic uncertainties for the primary and secondary, respectively. **Though we make an a priori assumption in our seismic modelling that the models are appropriate for the primary component, similar to the case of V380 Cyg, we still find mass discrepancy for the main-sequence secondary component of the σ Sco system.**

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